Beam Dynamics and Linac Simulation

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Fermilab Accelerator Advisory Committee

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Outline

- **Main specifications for the Linac**
- **Basic concepts for the Linac design**
  - RFQ
  - MEBT
  - Front end, 325 MHz
  - High energy section, 1300 MHz
- **Choice of lattice parameters**
- **High-intensity beam physics**
- **Detailed design and simulations**
- **Issues to be solved near future**
- **Conclusion**

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Main Linac Specifications

- **Provide 8-GeV $1.56 \cdot 10^{14}$ protons per cycle in the MI**
- **Beam time structure**
  - Extraction kicker -0.7 msec
  - Fit into MI 52.8 MHz rf structure without losses
- **Repetition rate & pulse length**
  - Initial configuration: 2.5 Hz at 3 msec, 0.5 MW at 8 GeV
  - **Ultimate configuration: 10 Hz, 1 msec, 2 MW at 8 GeV**
- **Consequences**
  - Peak current for beam dynamics design is 40 mA
  - Average current over the pulse is 25 mA
  - Fast chopper in the MEBT (rise/fall time ≤ 2 nsec)
  - Debuncher upstream of the MI

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8-GeV Linac conceptual design

- **RF power fan-out from one klystron to multiple cavity results in application of SC technology for the whole linac but an initial 10 MeV section**
- **Use two-frequency Linac option to produce multi-GeV hadron beams:**
  - Apply 1300 MHz ILC cavities above ~1.2 GeV
  - Develop and use S-ILC cavities (beta=0.81) in the energy range ~400 MeV-1.2 GeV
  - Spoke loaded SC cavities operating at ILC sub-harmonic frequency in the front end
- **Select sub-harmonic frequency for the front end: 1/4. Motivation: spoke loaded SC cavities are developed at ~345-350 MHz. Requires 30% less number of cavities compared to 433 MHz option. Klystrons are available from JHF developments.**
- **Below 10 MeV: use the RFQ and 16 RT-CH.**

Linac conceptual design (cont'd)

- **325 MHz SSR-1, SSR-2 and TSR from 10 MeV to ~418 MeV**

- **Apply SC solenoid focusing to obtain compact lattice in the front end including MEBT**

- **RFQ delivers axial-symmetric 2.5 MeV H-minus beam**

- **MEBT consists of 2 re-bunchers and a chopper. Smooth axial-symmetric focusing mitigates beam halo formation**

- **Beam matching between the cryostats: adjust parameters of outermost elements (solenoid fields, rf phase)**

- **In the frequency transition at ~418 MeV, matching in $(\varphi, \Delta W)$-plane is provided by 90° "bunch rotation"**

- **Avoid beam losses due to halo formation, machine errors and H-minus stripping**

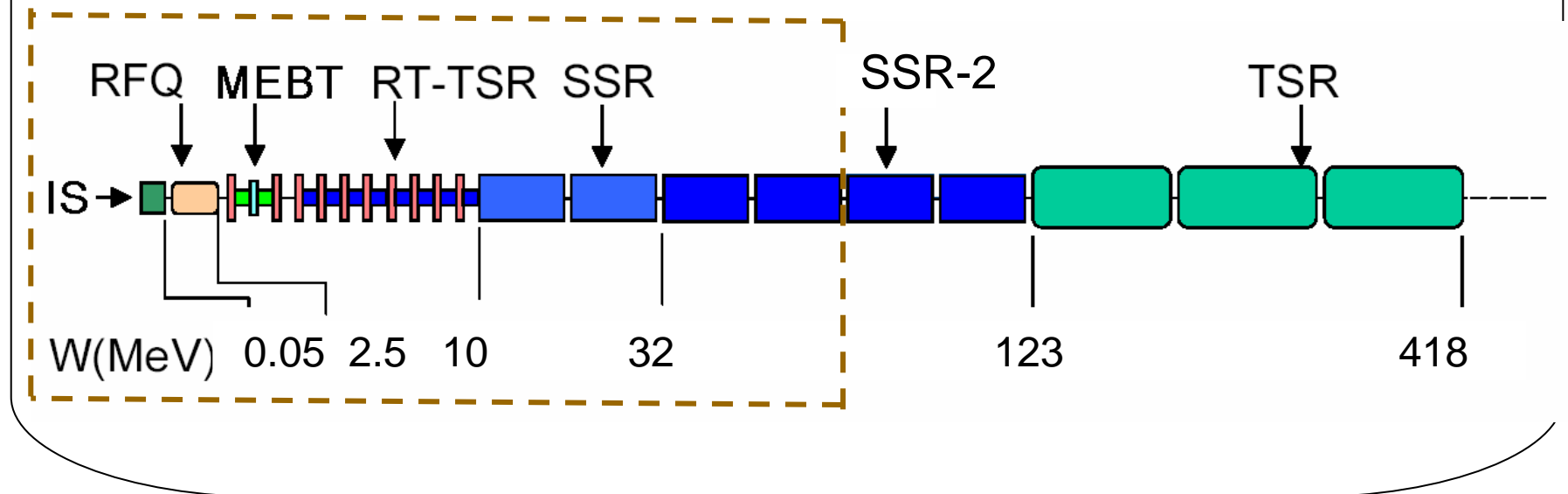# Linac Structure

Major Linac Sections

Radio Frequency Quadrupole

- **Well established accelerator (SNS, J-PARC,….)**
- **Basic PD requirements:**
  - Cost-effective   — **V.N. Aseev (ANL-PHY)**
  - Produce axially-symmetric beam   — **A.A. Kolomiets (ITEP, Moscow)**
  - Small longitudinal emittance

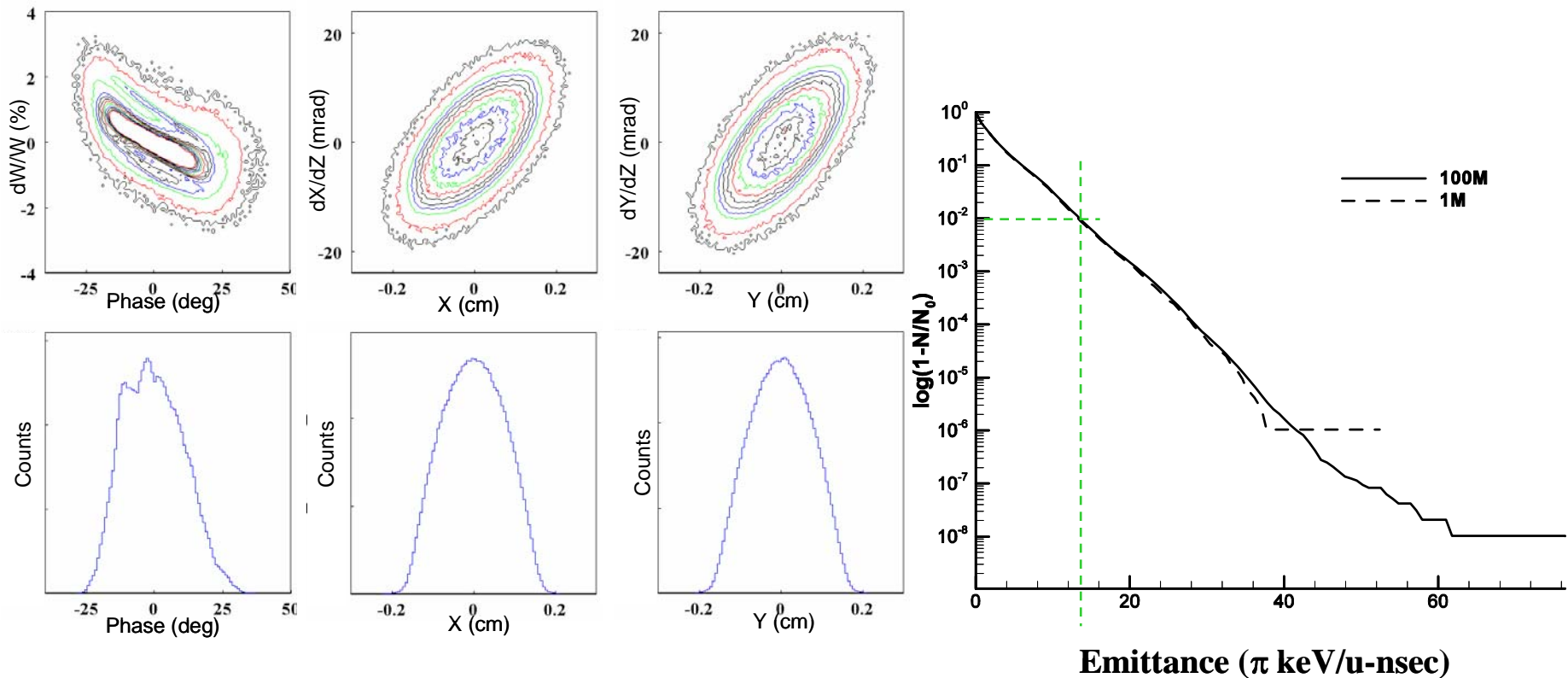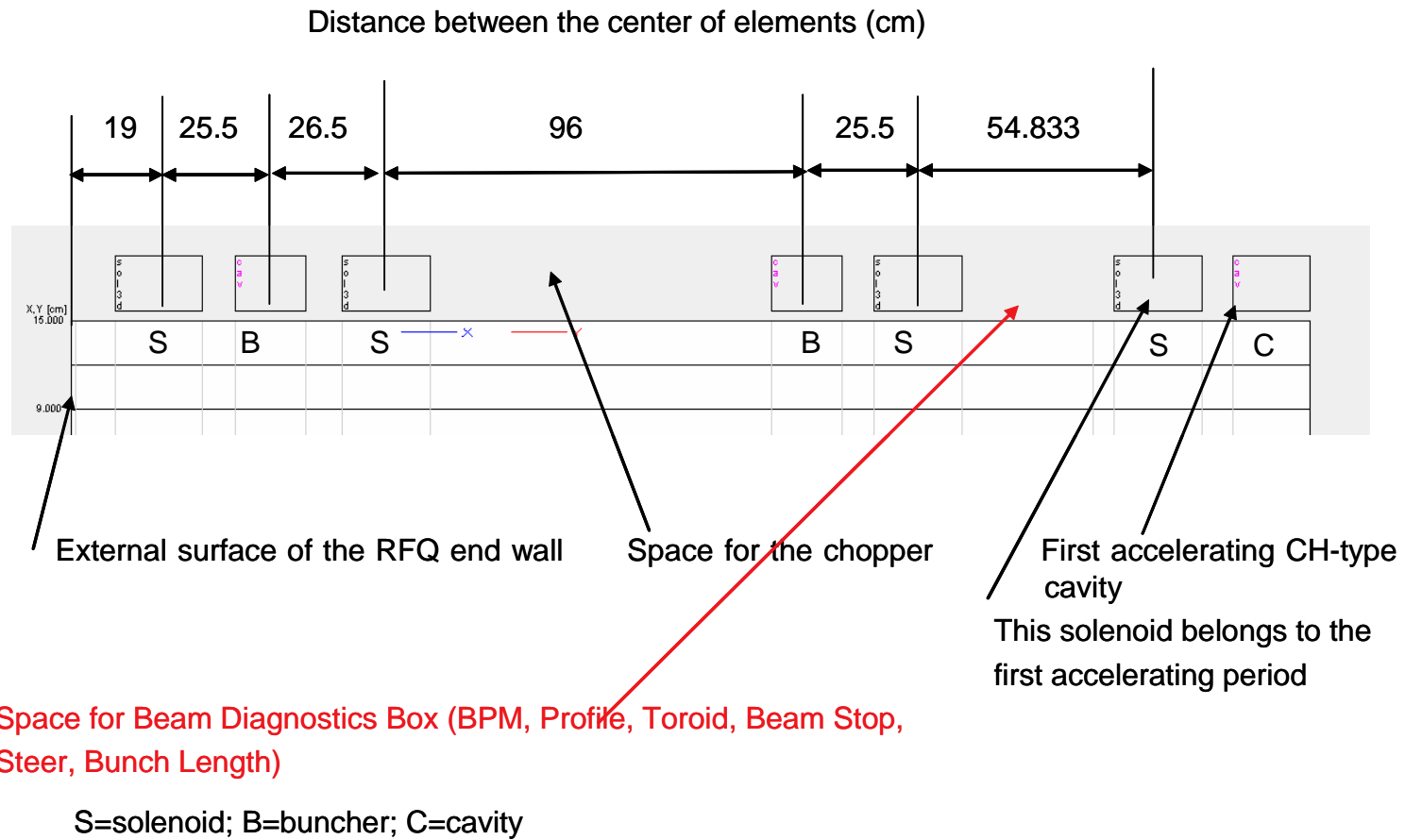|	
Average radius R_0, cm	0.340
Inter-vane voltage U_0, kV	90.45
Vane length, cm	302.428
Peak surface field, kV/cm	330
Output energy, MeV/u	2.498
Transverse emittance, rms, in/out, π mm mrad	0.10/0.10
Transverse emittance, 99.5%, in/out, π mm mrad	0.14/0.17
Long. emittance, rms, keV/u deg	133
Long. emittance, 99.5%, keV/u deg	1870
Transmission efficiency, %	97.8
Acceleration efficiency, %	95.9
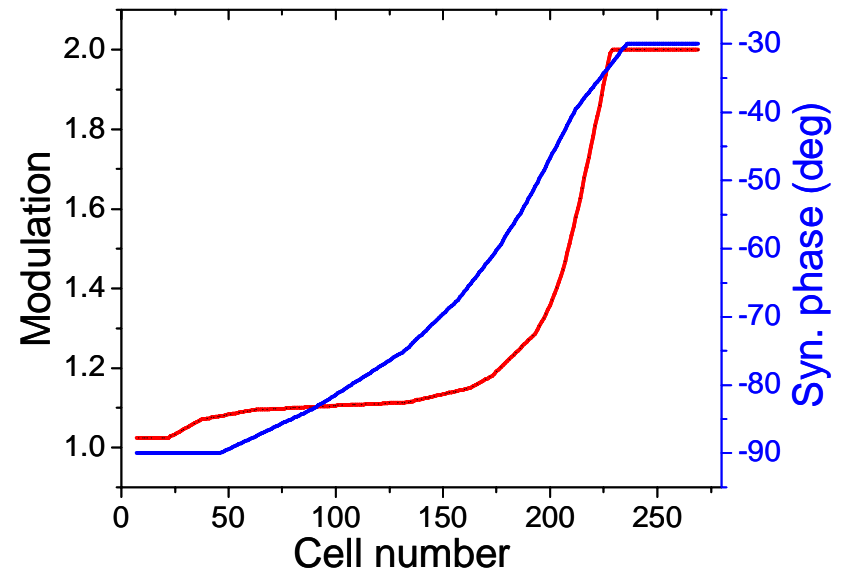
RFQ Beam Parameters (2.5 MeV, 43 mA)

Δφ-ΔW/W   XX′   YY′   Δφ-ΔW/W

MEBT

Distance between the center of elements (cm)

| 19 | 25.5 | 26.5 | 96 | 25.5 | 54.833 |

External surface of the RFQ end wall   Space for the chopper   First accelerating CH-type cavity

This solenoid belongs to the first accelerating period

Space for Beam Diagnostics Box (BPM, Profile, Toroid, Beam Stop, Steer, Bunch Length)

S=solenoid; B=buncher; C=cavity

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Chopper

Pulser voltage ± 1.9 kV

Rep. rate 53 MHz

Rise/fall time ≤ 2 nsec (at 10% of the voltage level)

Beam target power: 37 kW pulsed, 370 W average

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High intensity beam physics

- **Phase advances of transverse oscillations for zero current beams must be below 90°**
- **Wave numbers of oscillations must change adiabatically along the linac despite of many lattice transitions with different types of focusing and inter-cryostat spaces, cavity TTF.**
- **Avoid strong space charge resonances (Hoffman's Chart)**
- **Provide equipartitioning of betatron and synchrotron oscillation temperatures along the linac, primarily in the front end**
- **Beam matching in the lattice transitions is very important to avoid emittance growth and beam halo formation**
- **Short focusing periods in the Front End**
- **Analyze HOM and avoid excessive power losses on cavity walls**

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Properties of an ion SC linac

- **The acceleration is provided with several types of cavities designed for fixed beam velocity. For the same SC cavity voltage performance there is a significant variation of real-estate accelerating gradient as a function of the beam velocity.**

- **The length of the focusing period for a given type of cavity is fixed.**

- **There is a sharp change in the focusing period length in the transitions between the linac sections with different types of cavities**

- **The cavities and focusing elements are combined into relatively long cryostats with an inevitable drift space between them. There are several focusing periods within a cryostat.**

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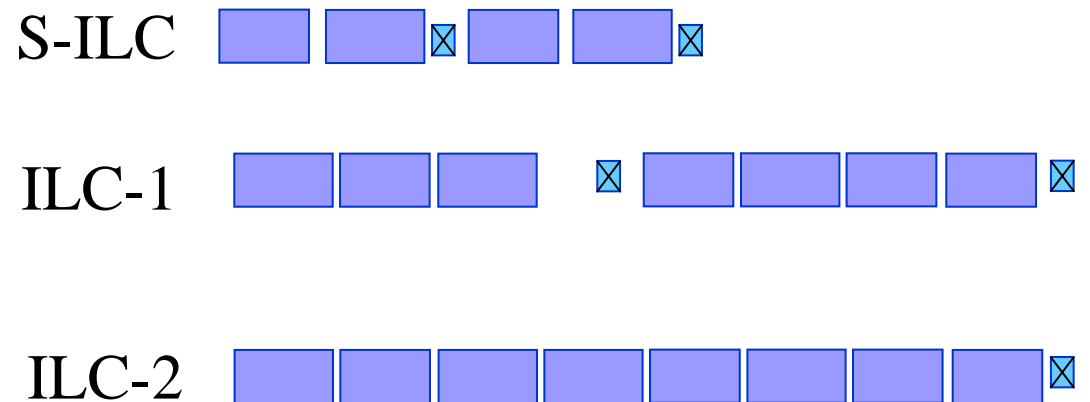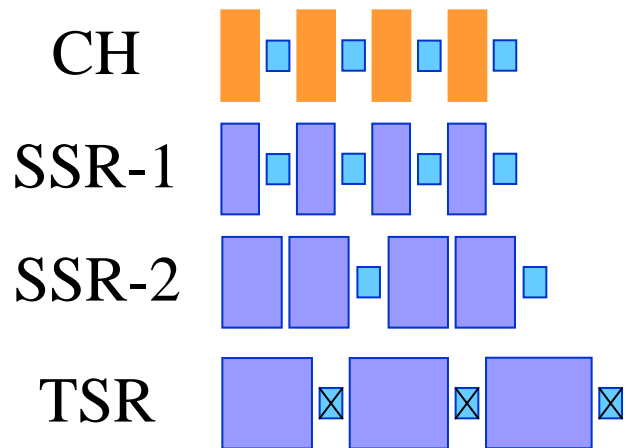# Iterative procedure of the lattice design

- Select the type and geometric beta of the cavities using a simplified formula for the cavity TTF. Optimize the electrodynamics and the mechanical design of the cavities. By numerical simulation, design the cavities to reduce the ratio of peak surface fields to the accelerating field.

- Assume experimentally proven peak surface fields in SC cavities.

- Select the focusing lattice. Select the cryostat length and inter-cryostat spaces working with cryogenic and mechanical engineers.

- Develop lattice tuning for the beam without space charge.

- Using rms envelope equations check the lattice tune to verify and avoid strong space charge resonances.

- Provide matching of the beam for the design peak current in all lattice transitions.

- Simulate beam dynamics using multi-particle codes. Study beam losses using a large number of multi-particles, $\sim 10^6$.

- Iterate this procedure to obtain a linac design which satisfies the engineering requirements and provides high quality beams.

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Accelerating cavities
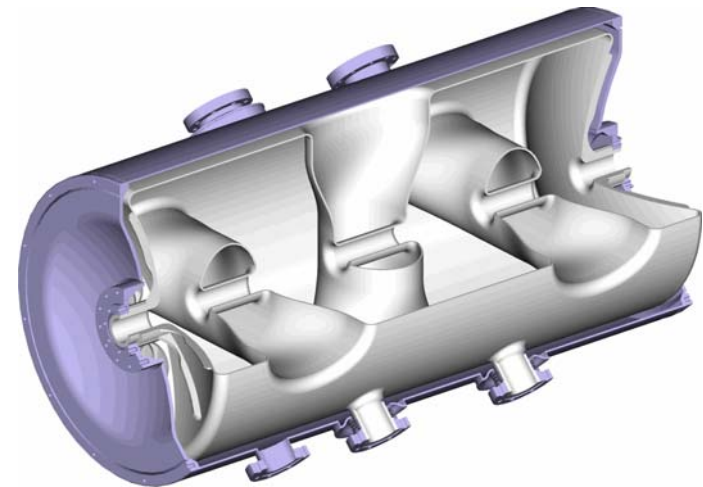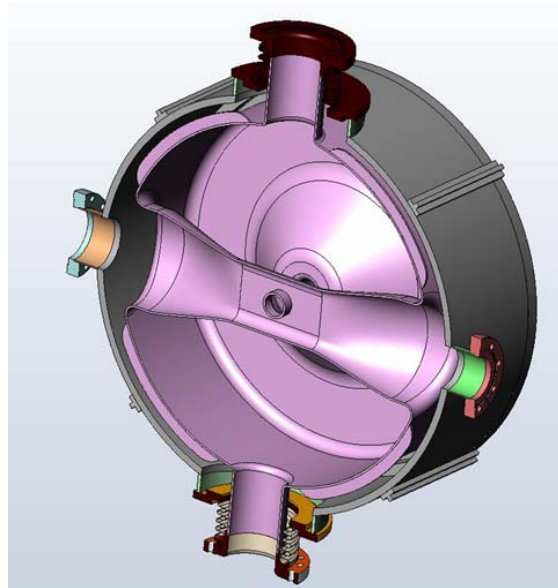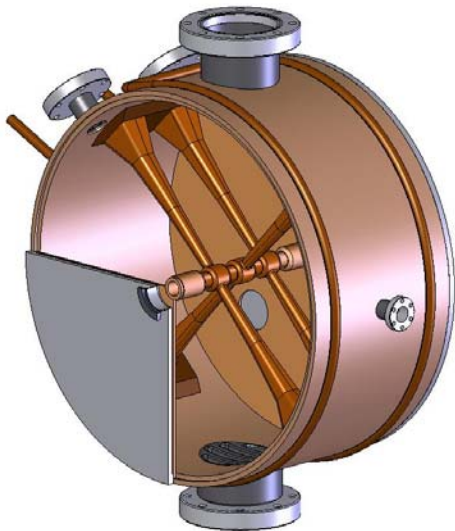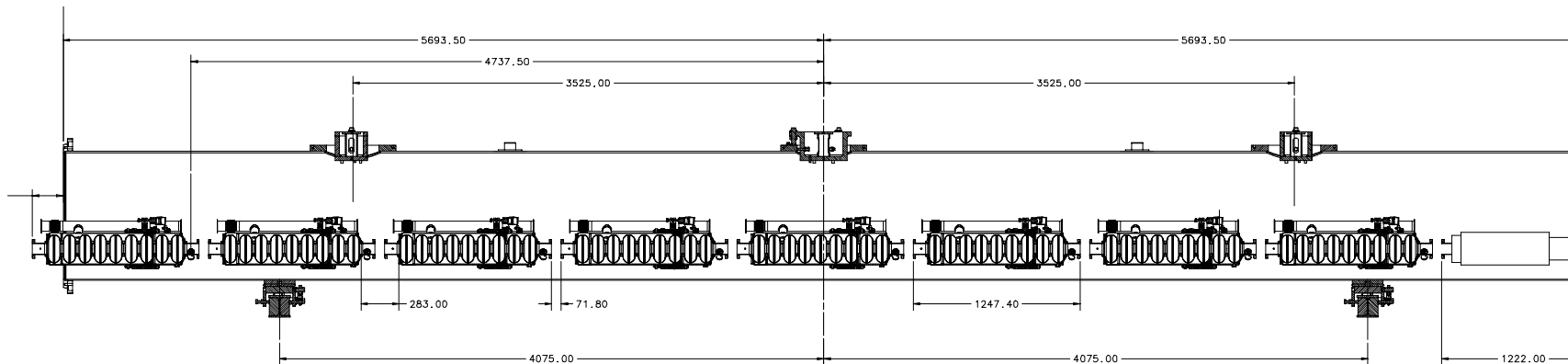
Cavity parameters and focusing lattice

Section	CH	SSR-1	SSR-2	TSR	S-ILC	ILC-1	ILC-2
β_G	-	0.2	0.4	0.6	0.83	1	
# of res.	16	18	33	42	56	63	224
# of cryost.	-	2	3	7	7	9	28
E_{peak} (MV/m)	-	30	28	30	52	52	
Focusing	SR	SR	SRR	FRDR	$FR^2DR^{2\,*}$	FR^4DR^3	FR^8DR^8
$L_{Focsuing}$, m	0.515-0.75	0.75	1.6	3.81	6.1	12.2	24.4

CH

SSR-1

SSR-2

TSR

S-ILC

ILC-1

ILC-2

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Voltage gain per cavity

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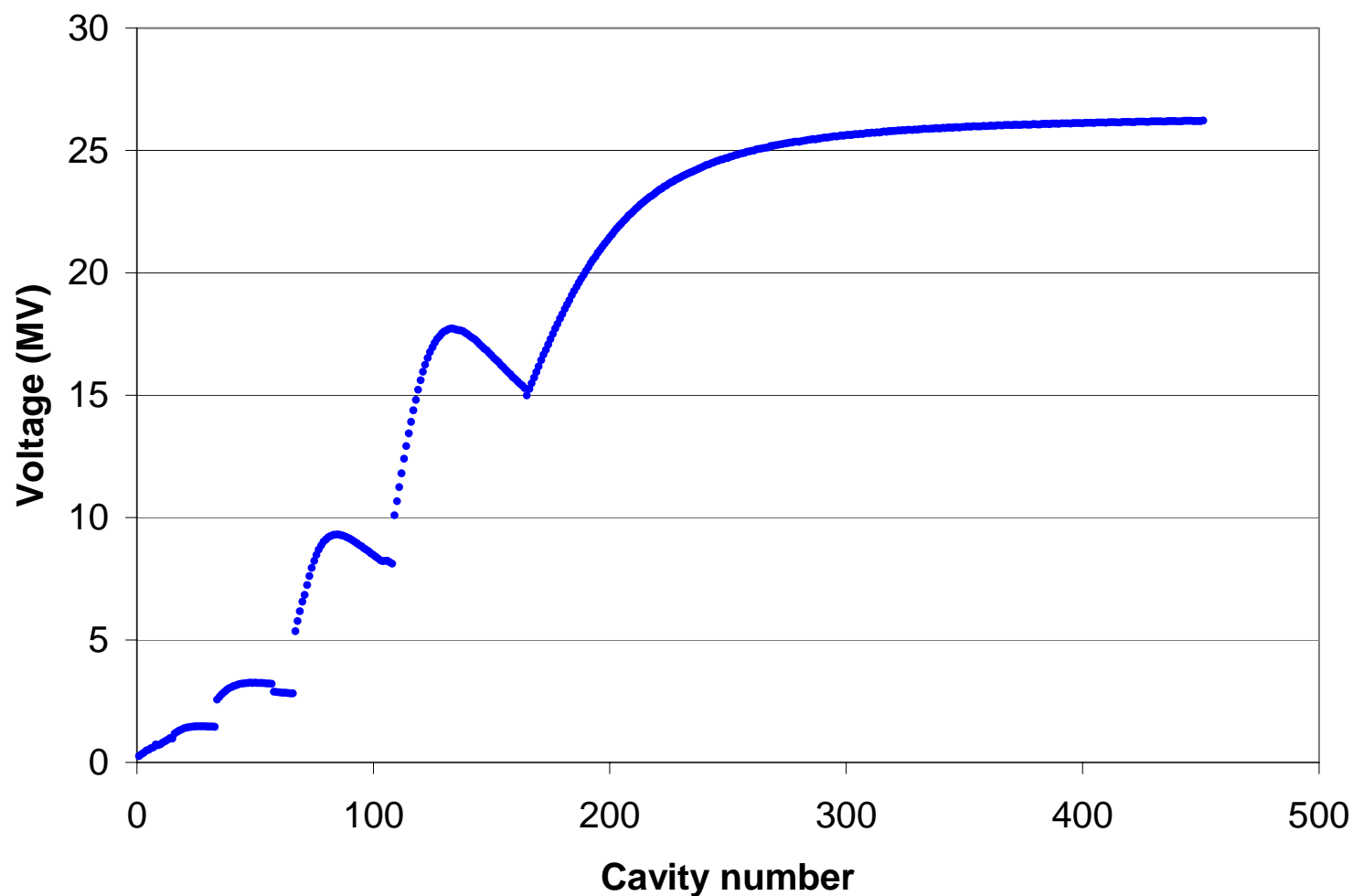
Stability diagram (betatron oscillations)

Axis label (y): $\cos(\sigma_T)$

Axis label (x): Defocusing factor
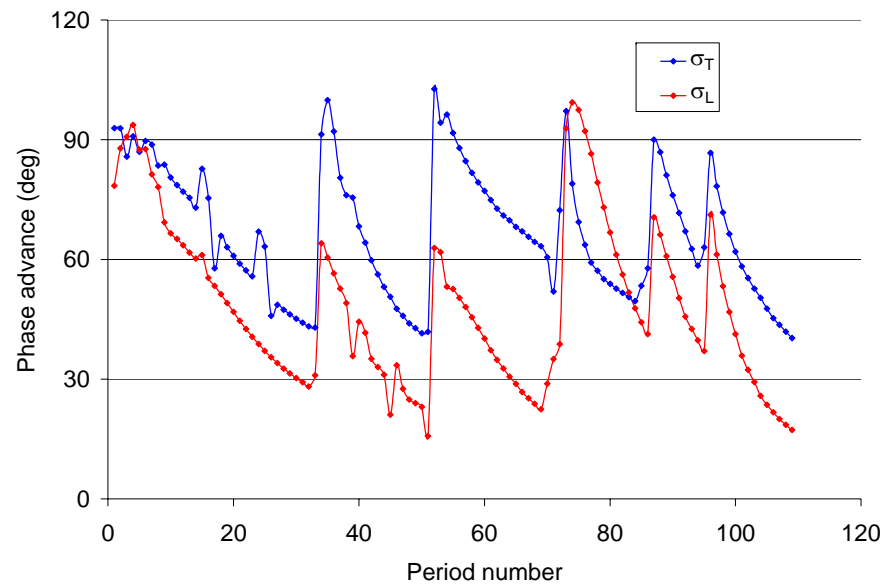
Legend:
- PR
- SPh
- CH
- SSR-1
- SSR-2
- TSR
- S-ILC
- ILC

$$\Delta_s = \frac{\pi}{2} \frac{1}{(\beta\gamma)^3} \frac{S_f^2}{\lambda} \frac{eE_m \sin \varphi_s}{m_0 c^2}$$
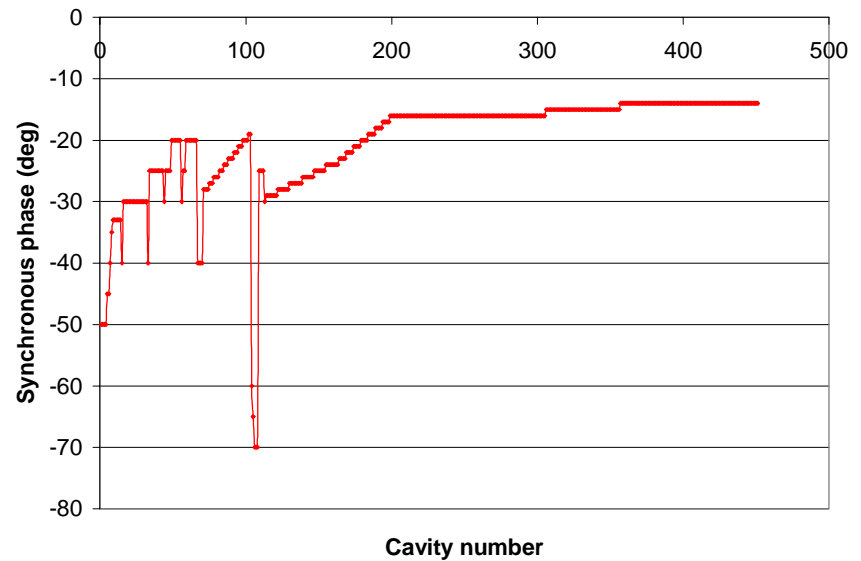
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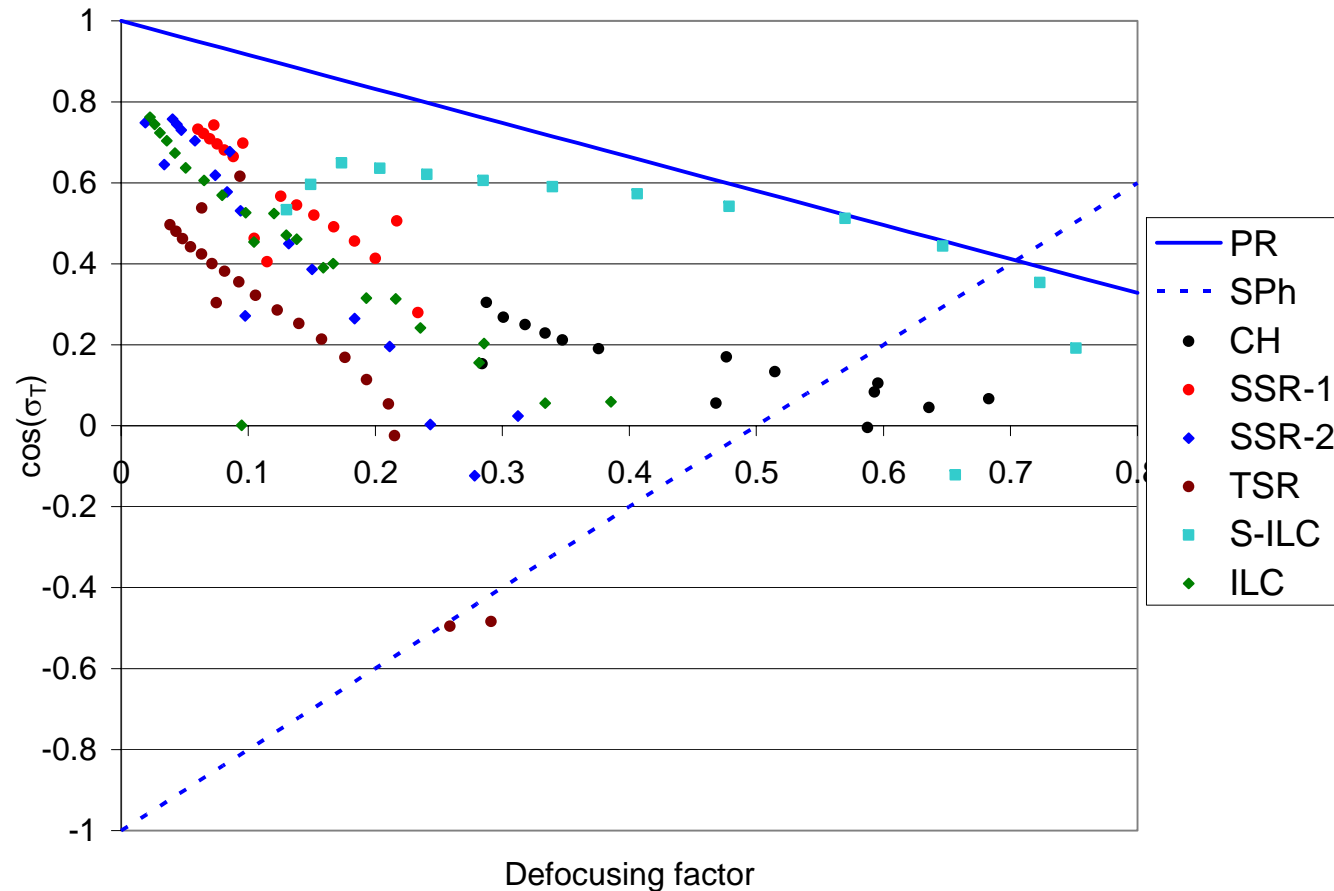
Wave numbers of T- and L- oscillations
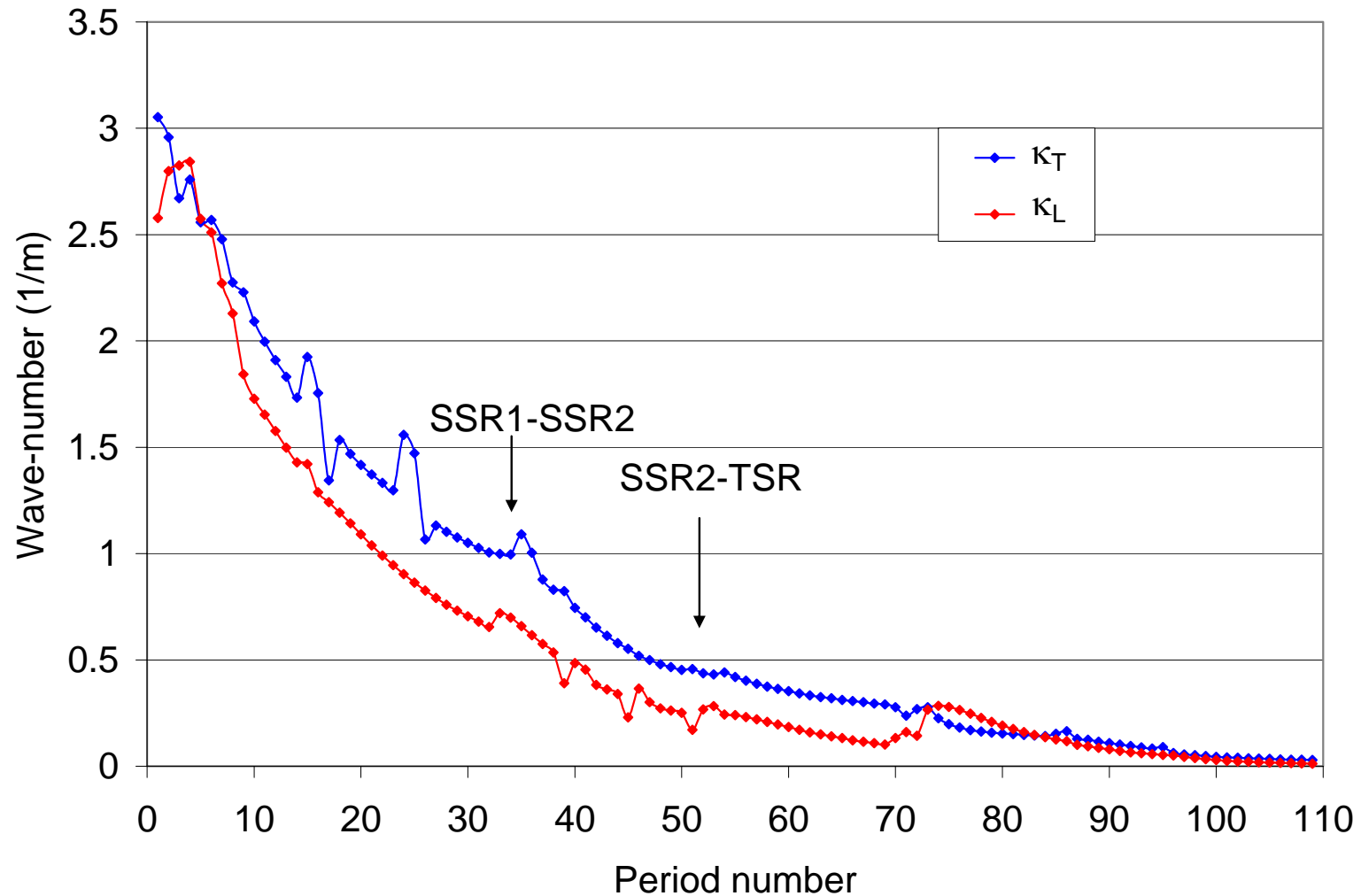
Linac parameters variation

Phase advance

Synchronous phase

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Peak RF power per cavity

Due to high shunt impedance, the RT-CH cavities dissipate less rf power than a DTL cavity by a factor of 2

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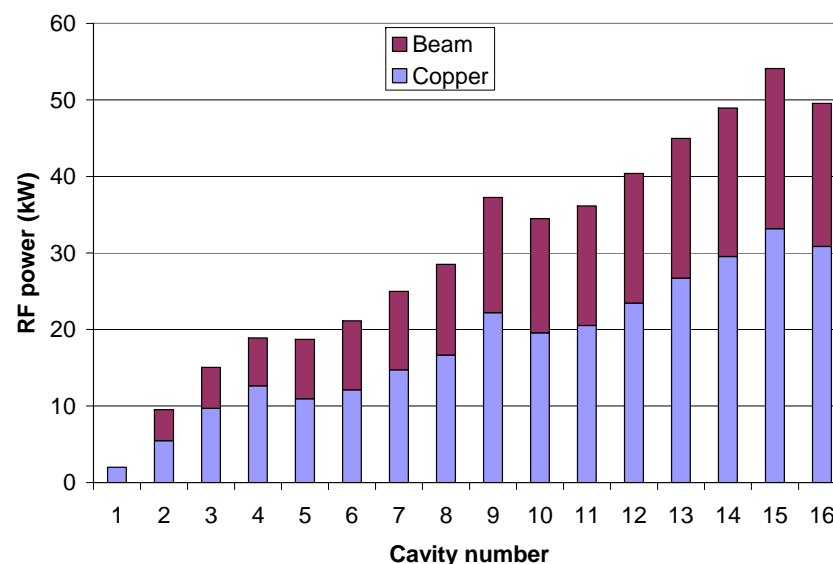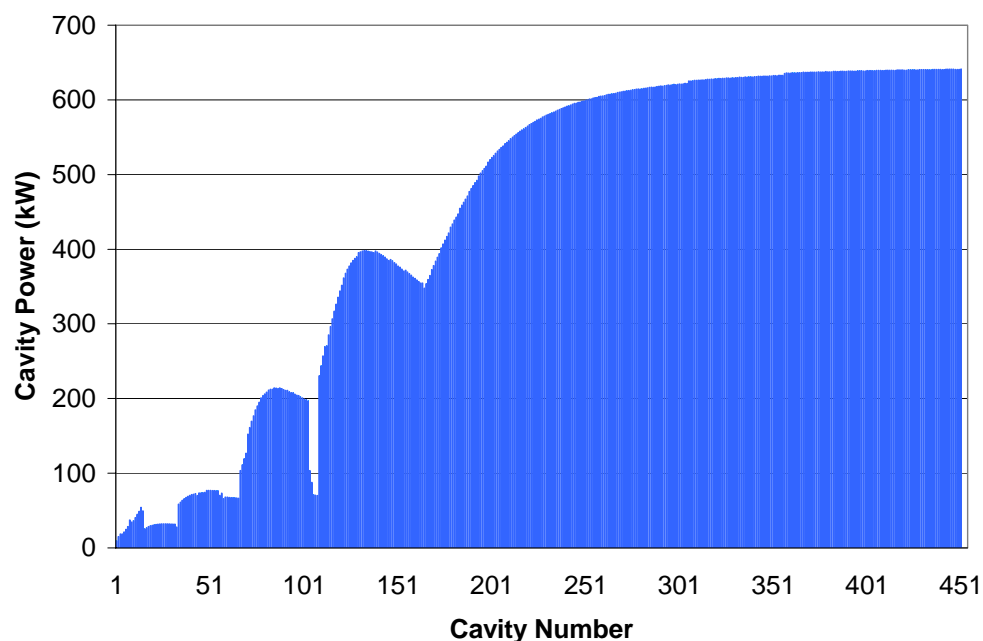
End-to-end simulations

- **End-to-end simulations: the TRACK code. In the RFQ - 10^8, LINAC- 10^6 macro-particles**

- **All fields are 3-D, resonator's fields - MWS, solenoid fields – EMS**

- **Lattice is tuned for 45 mA - (RFQ), 43.25 mA - linac**

- **Some earlier designs have been simulated including machine errors, 100 seeds, 40K particles in each seed**

- **Linac simulations cross-check by using several codes:**
  - TRACK, ANL (main workhorse)
  - ASTRA, DESY code, J.-P. Carneiro (FNAL-AD)
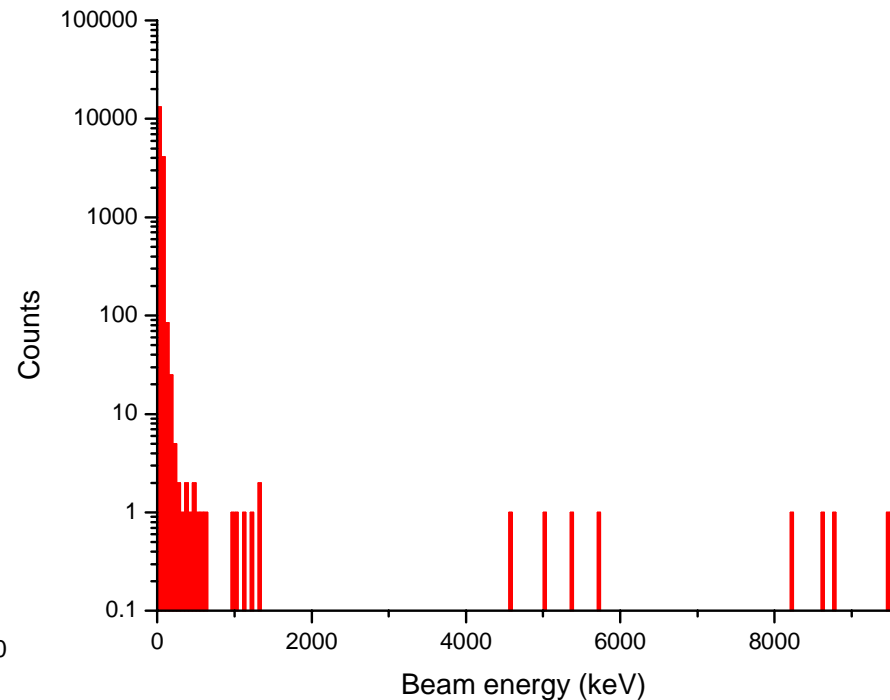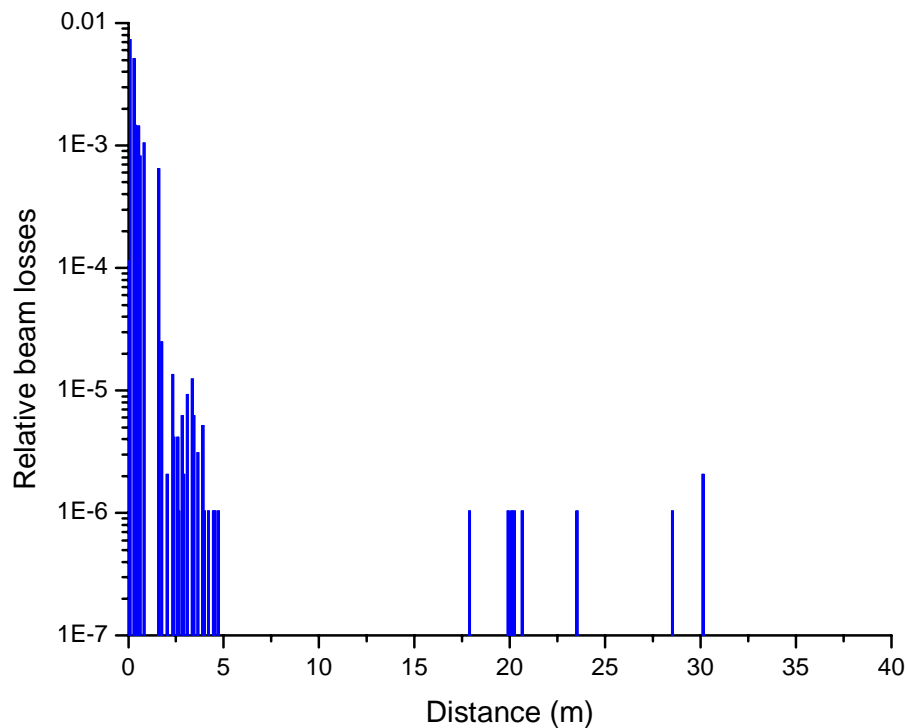 - IMPACT, LBNL/LANL code, B. Mustapha (ANL-Physics)

Beam envelopes, 43 mA

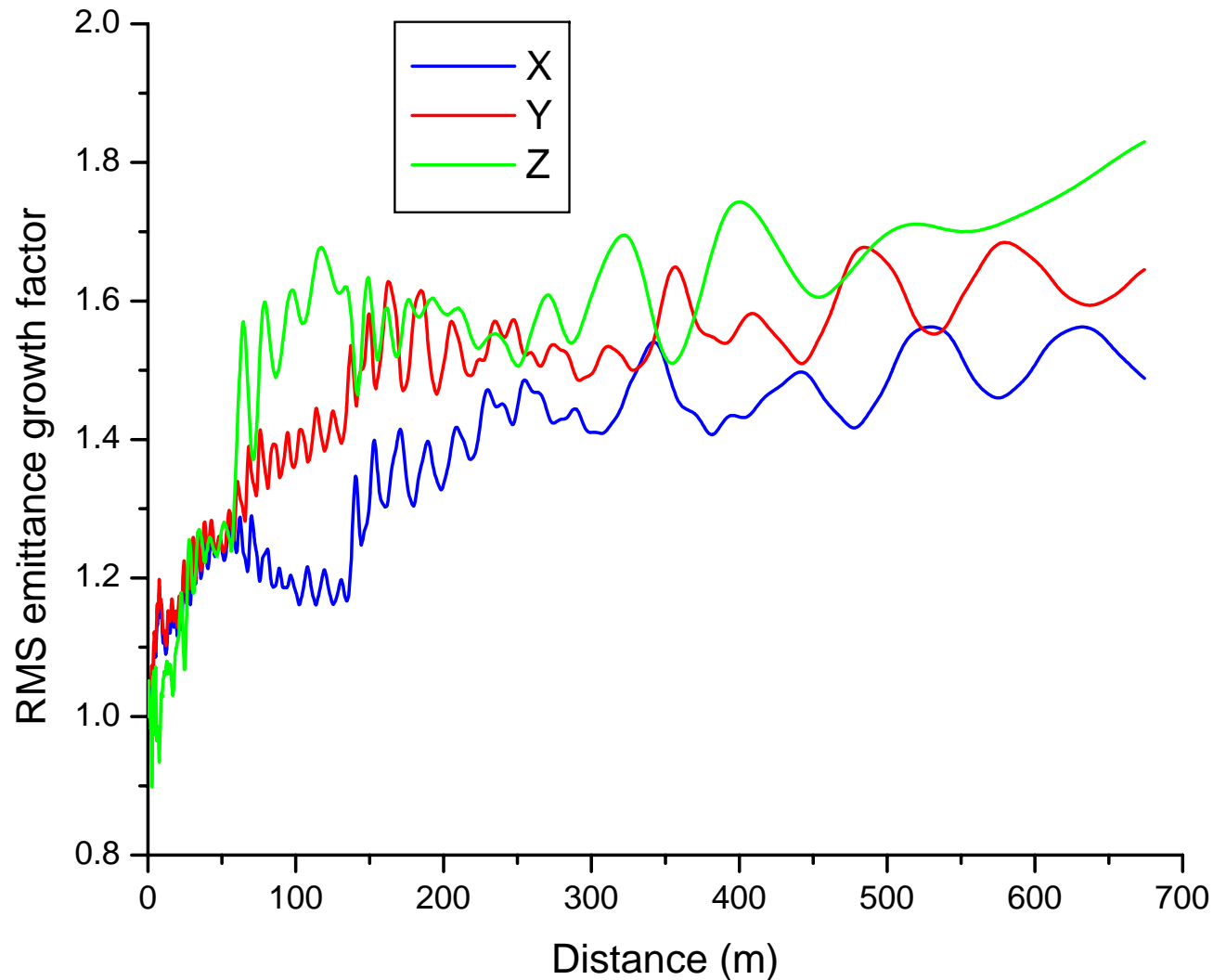Fermilab   Argonne NATIONAL LABORATORY   Physics Division
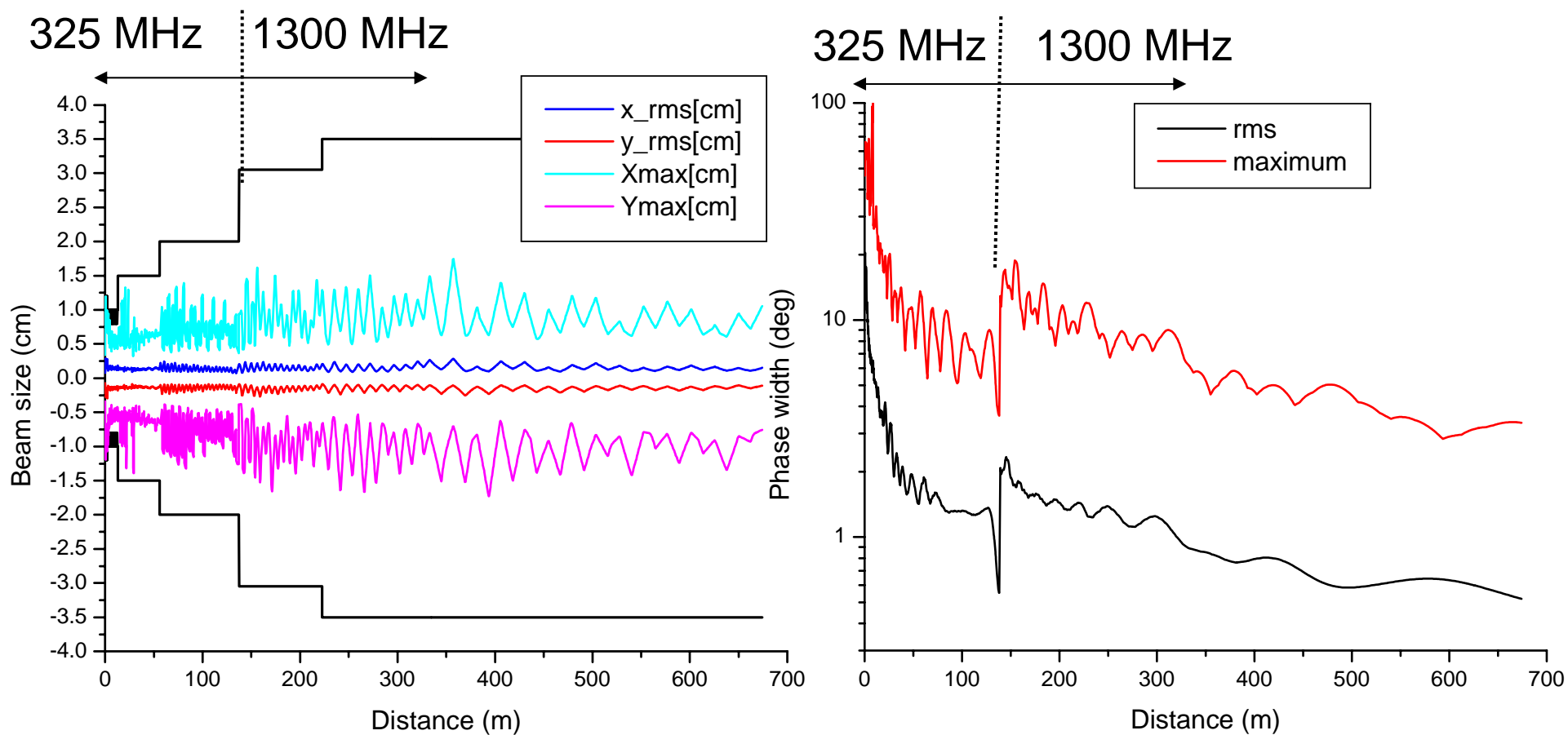
Beam losses (MEBT and RT)

~1.8% are lost in the MEBT, particle energy <1.4 MeV 8 particles out of million are lost in the RT section, particle energy 4-10 MeV
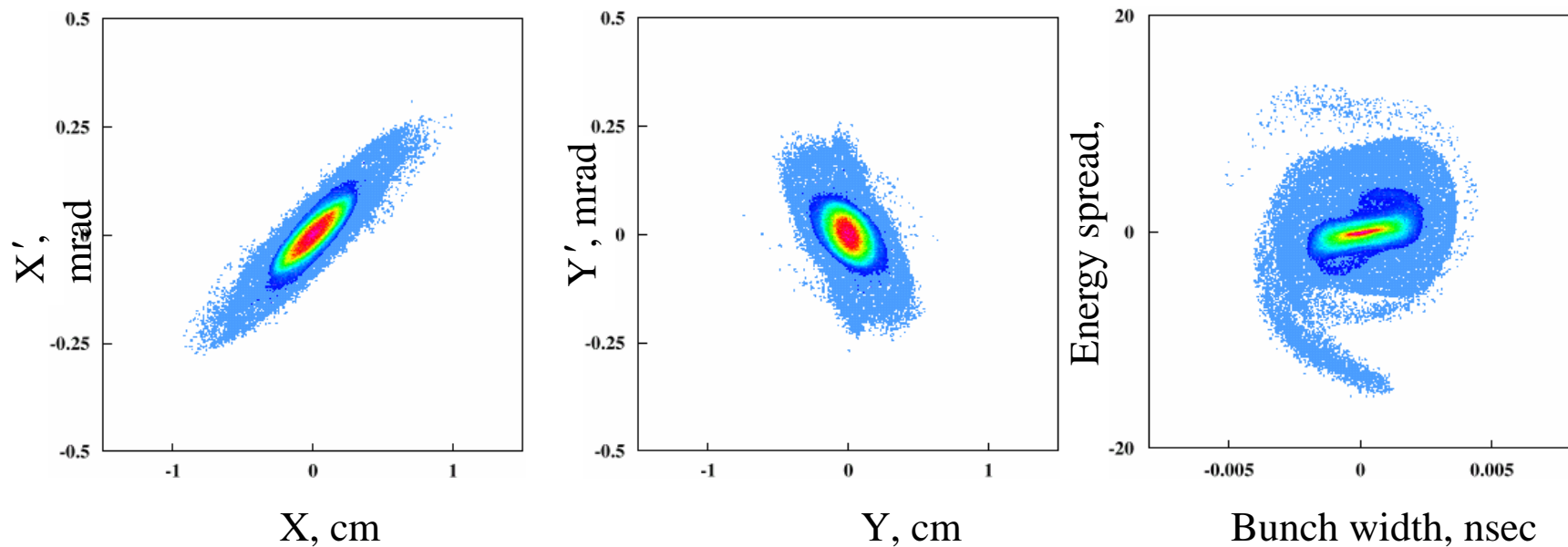

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RMS emittance growth (43 mA)

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Phase space plots (8-GeV, 43 mA)

Image of 1 million particles at the end of Linac without errors

$$\frac{\text{Total emittance}}{\text{RMS emittance}} = 50 \qquad\qquad 95 \qquad\qquad 85$$

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High statistics simulations with rf errors

Image of 40 million particles at the end of Linac with rf errors
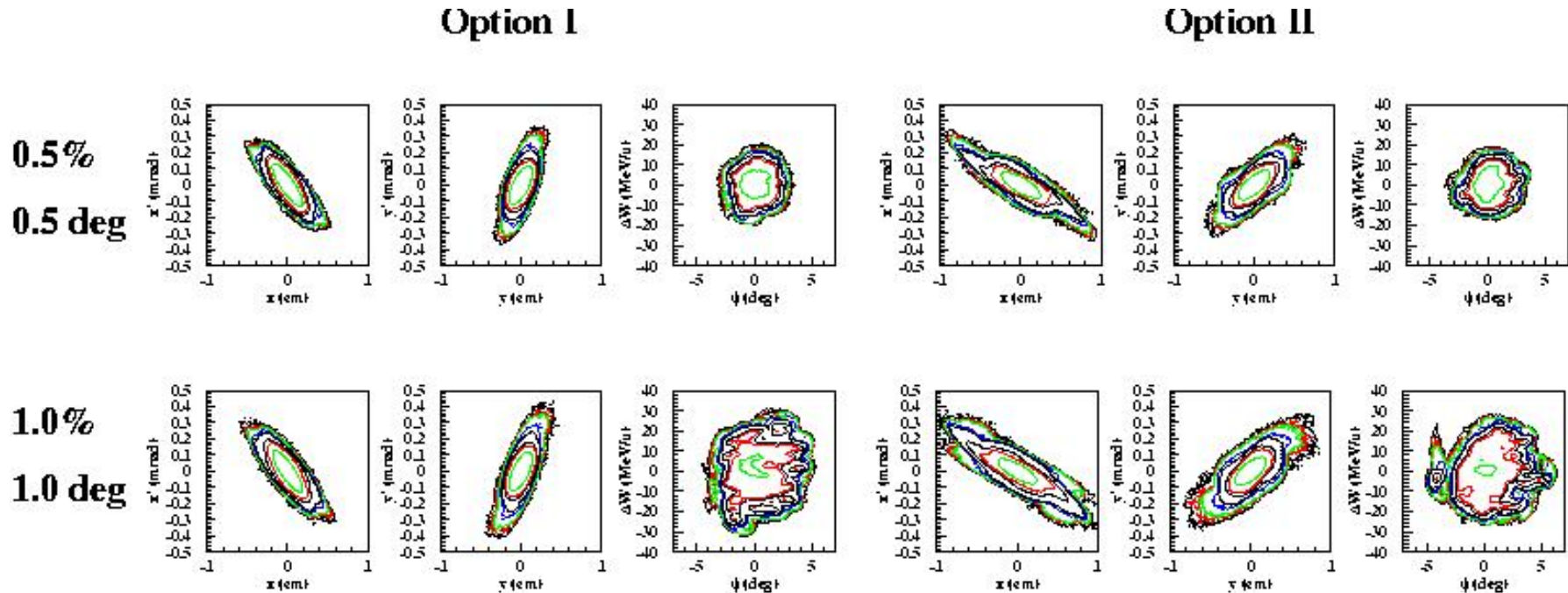
- ➢ **Option I is more tolerant to jitter errors**
- ➢ **Option II: kind of beam halo formation for (1.0%, 1 deg), may require more careful design optimization.**

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Energy Jitter Correction (1.0%, 1.0°)

It is more efficient to place the debuncher at the end of the 972.5 m drift between the Linac and the Main Injector.

The required voltage is:
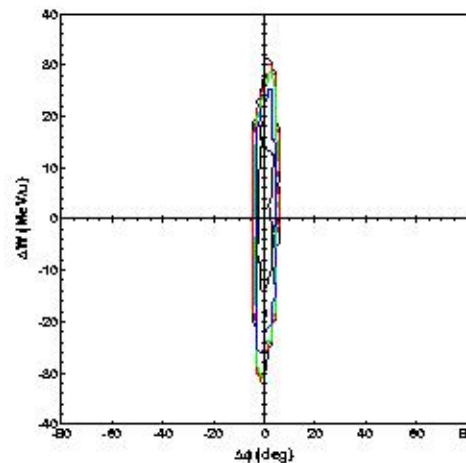
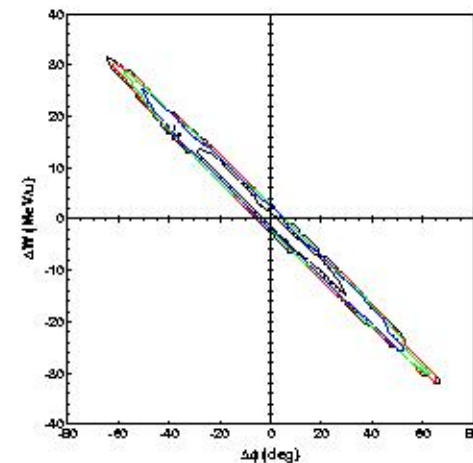27.5 MV same as for (0.5%, 0.5 deg)

After correction:

the energy width is

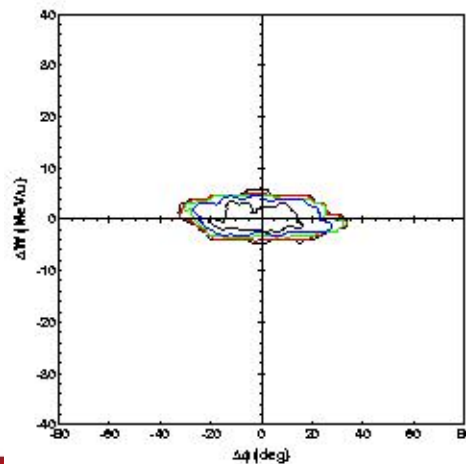+/- 3 MeV , the phase width is +/- 65 deg of 1300 MHz (130 deg total = 0.28 ns).
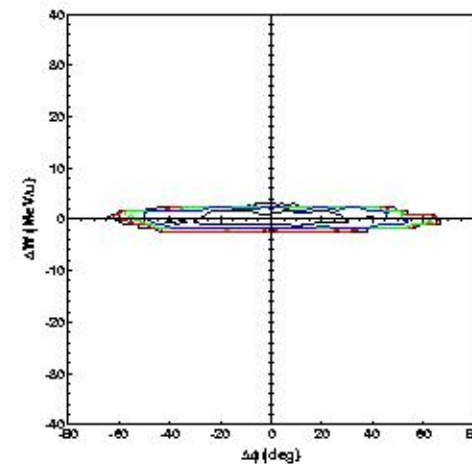

Exit of Linac

Entrance of Main Injector

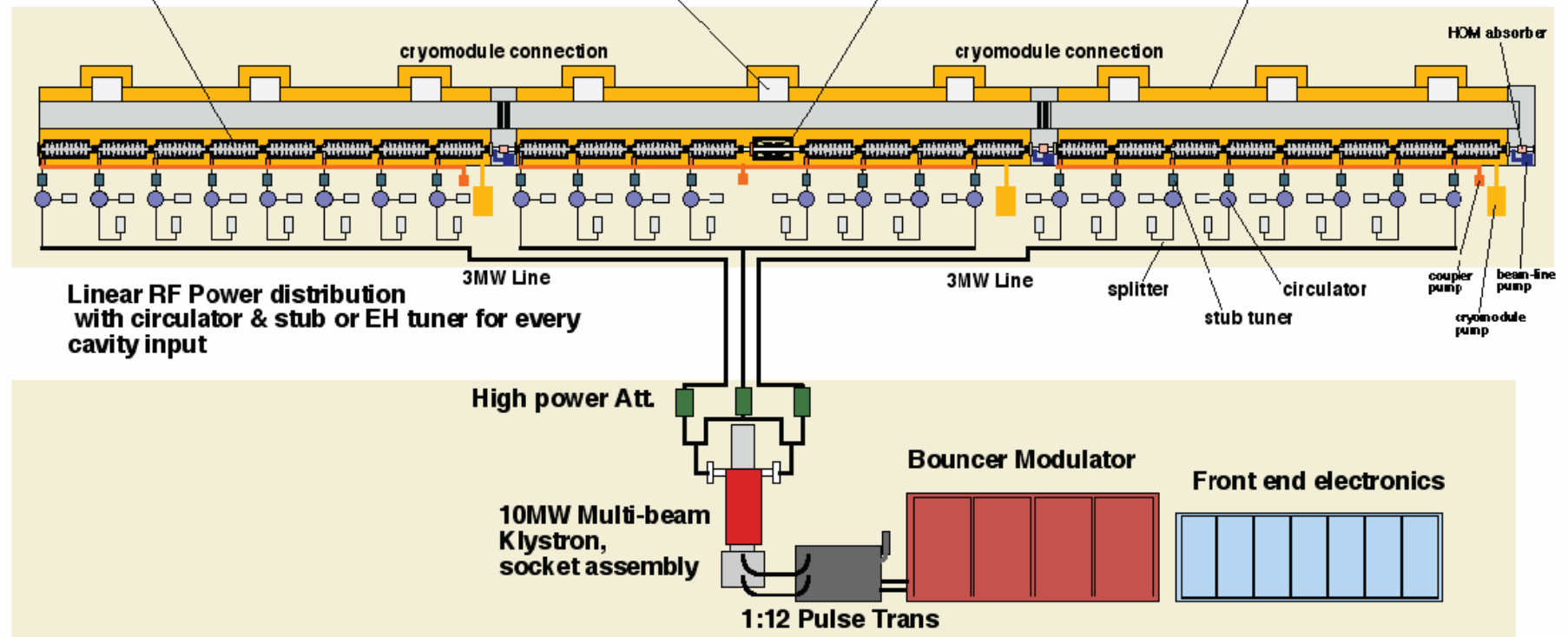**Debuncher: half-way, 55 MV**

Debuncher: at the end, 27.5 MV

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Recent ILC Lattice

Beam dynamics in the new ILC lattice

Simulation of 20K particles, 43.25 mA – NO beam losses

Simulation of 1M part., 43.25 mA – $2 \cdot 10^{-5}$ relative losses (~13 Watts local beam losses)

3.2 GeV, 8 ILC RF Units

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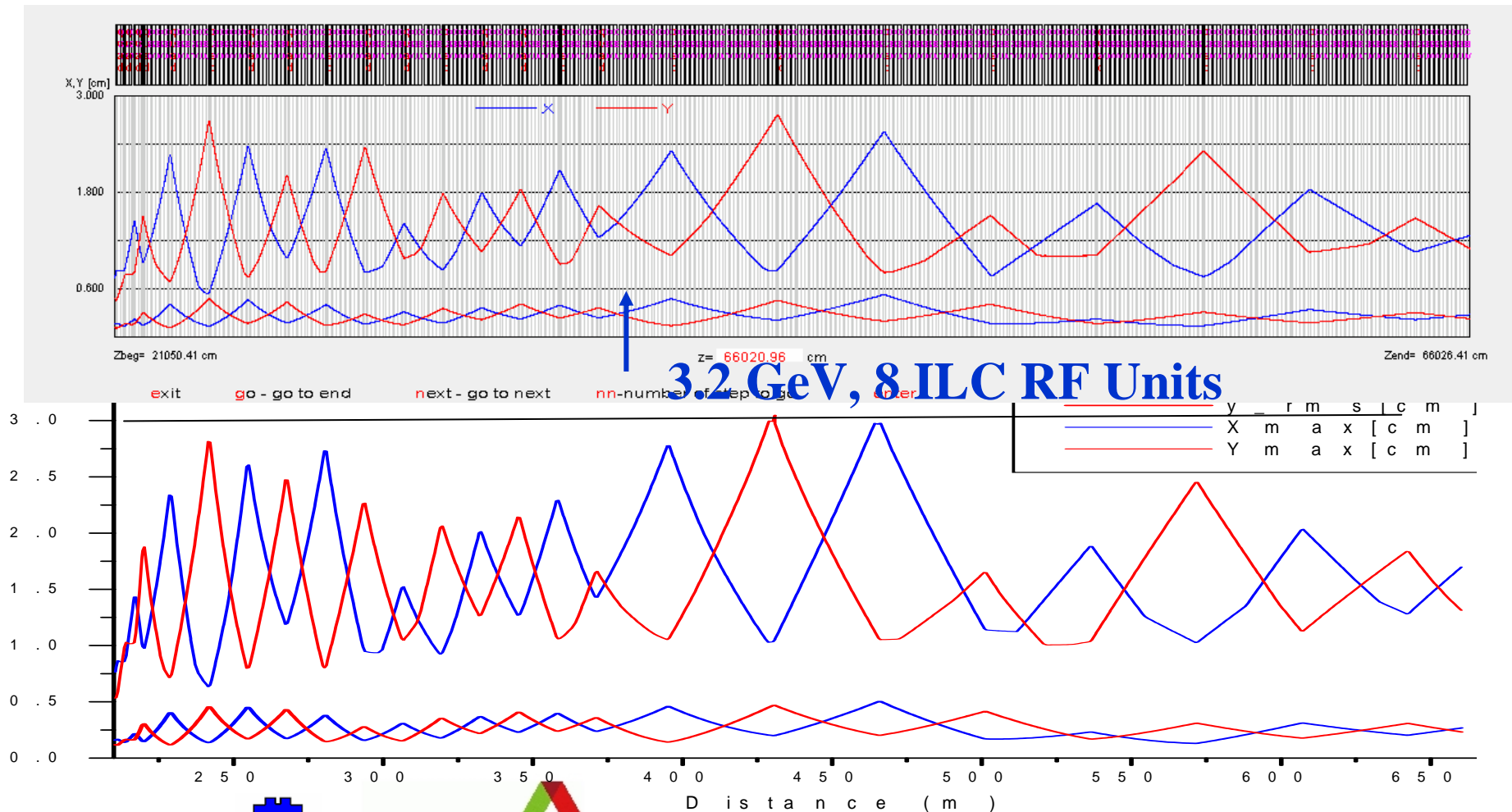
Future work

- **Integrated lattice design should be continued: beam physics; mechanical, cryogenic design; implement ILC lattice directly for H-minus acceleration, work with current version of the ILC cryostat design**
- **Finalize beam diagnostics specifications**
  - Develop beam tuning & commissioning procedures
- **High-statistic machine error studies on parallel computer**
  - Beam correction
- **Study of different options of the linac to provide the most cost-effective design**
  - Example: frequency transition energy (110 MeV vs 420 MeV)
- **Detailed studies of HOM in ILC-style cavities and in the TSRs**
- **Code developments**
  - Implement FVM feedback model (SCREAM-1D code) into the TRACK code (3D, parallel computing)
  - fitting in realistic fields with space charge
  - Include all H-stripping mechanisms

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CONCLUSIONS

- **New approach in hadron Linacs - "Pulsed SC Front End"-provides high-quality beams**

- **The concept of "current-independent" tune works well for the SC Linac: the same "43-mA tune" is good for all beam currents in the range from 0 to 43 mA**

- **Baseline design of the 8-GeV Linac: no beam losses (except H-minus stripping) at present stage of the simulations**

- **Preliminary study shows that 5 modules (15 cryostats, 120 cavities) of the new ILC RF unit can be used in the high energy end of the linac**

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